

Strong interaction between light and a single trapped atom without a cavity

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Many quantum information processing protocols require efficient transfer of quantum information from a flying photon to a stationary quantum system. To transfer information, a photon must first be absorbed by the quantum system. A flying photon can be absorbed by an atom residing in a high-finesse cavity with a probability close to unity. However, it is unclear whether a photon can be absorbed effectively by an atom in a free space. Here, we report on an observation of substantial extinction of a light beam by a single ⁸⁷Rb atom through focusing light to a small spot with a single lens. The measured extinction values are not influenced by interference-related effects, and thus can be compared directly to the predictions by existing free-space photon-atom coupling models. Our result opens a new perspective on processing quantum information carried by light using atoms, and is important for experiments that require strong absorption of single photons by an atom in free space.

Strong interaction between light and matter is essential for successful operation of many quantum information protocols such as quantum networking^{1,2}, entanglement swapping between two distant atoms³⁻⁵, and implementation of elementary quantum gates⁶. These protocols consider quantum states of localized carriers (nodes) like atoms, ions, or even atomic ensembles, that exchange information through a quantum channel with help of “flying” qubits (photons). The quantum channels can be implemented via well-defined photonic modes that couple the nodes with high efficiency. For example, in the original proposal for quantum networks¹, atoms were placed in high-finesse cavities that not only provide a strong interaction between a photon and an atom, but also ensure that most of the spontaneously emitted photons are collected into the same mode. Experimental advances in atom-photon cavity QED indeed allowed the information exchange between an atom and single photons in this configuration to be carried out with high efficiency⁷⁻¹¹. However, scaling such a scheme to many localized nodes is experimentally difficult, since managing the losses and coupling of the intra-cavity field of high-Q cavities to propagating modes of flying qubits is already quite challenging.

In an attempt to avoid the complications connected with cavities, one could consider an interface between stationary and flying qubits in a simpler free-space configuration, where the quantum

channel is defined e.g. by a Gaussian mode of a single mode optical fiber, and a single atom is strongly coupled to this mode with help of a large numerical aperture lens. Indeed, the common model describing the interaction of a monochromatic plane wave with a two-level atom predicts a scattering cross section of $\sigma = 3\lambda^2/2\pi$. This area is close to a diffraction limited spot size of a lens with a large numerical aperture, hence suggesting a high coupling efficiency¹² for such a system. On the other hand, for strong focusing where substantial coupling might be expected, one has to carefully consider the electric field strength and polarization within the focal ‘spot’^{13,14} because an atom essentially interacts only with the field at its location. The conclusion from such an attempt¹³ was that for realistic lenses, only a low coupling efficiency can be accomplished. In view of those two contradicting opinions, we experimentally quantified the coupling efficiency between a focused light beam and a single atom without a cavity using a simple transmission measurement setup.

The first transmission spectrum of a single atom was observed for a $^{198}\text{Hg}^+$ ion¹⁵. There, the absorption probability of the probe photons was estimated to be about 2.5×10^{-5} . Recently performed experiments on single molecules and semiconductor quantum dots^{16–18} reported a signal contrast up to 13%. However, these results do not reflect the actual extinction of the excitation beam by the quantum systems directly, since the signals observed were enhanced using the interference between the light scattered by the single quantum systems and part of the excitation light beam. The main idea of our setup is to focus a weak and narrow bandwidth Gaussian light beam (probe) onto a single ^{87}Rb atom using a lens. Part of the probe is scattered by the atom. The remaining part is fully collected by a second lens in the downstream direction, and delivered to a single photon detector. Compared to the previous experiments, our setup allows us to *directly* measure the extinction of a probe beam by a single atom (see methods) free of interference enhancement effects. The extinction value obtained this way sets a lower bound to the scattering probability of the light by the atom (see methods).

Figure 1 shows the schematic diagram of our experiment. The heart of the setup consists of two identical aspheric lenses (full NA = 0.55, $f = 4.5$ mm), mounted in a confocal arrangement inside an ultra high vacuum chamber. The Gaussian probe beam is first delivered from a single mode fiber, focused by the first lens, fully collected by the second lens, and finally coupled again into a single mode fiber connected to a Si-avalanche photodiode. A ^{87}Rb atom is trapped at the focus between the two lenses by means of a far-off-resonant optical dipole trap (FORT) formed by a light beam ($\lambda = 980$ nm) passing through the same lenses. Cold atoms are loaded into the FORT from a magneto optical trap (MOT) surrounding the FORT. In this experiment, the FORT beam has a waist of $1.4 \mu\text{m}$ at the focus²⁶. The maximal trapping potential at the center of the FORT is about $h \cdot 27$ MHz. Due to the small size of the FORT, a collisional blockade mechanism allows no more than one atom in the trap at any time^{21,22}. To confirm the single atom occupancy of the trap, we extract the second order correlation function $g^{(2)}(\tau)$ from the fluorescence of the trapped atom exposed to the MOT beams with the help of detectors D1 and D2 that couple to the atom from opposite directions through the same Gaussian mode (Fig. 1). Figure 2 shows the histogram of the time delays between photodetection events at detectors D1 and D2. It reveals a Rabi oscillation

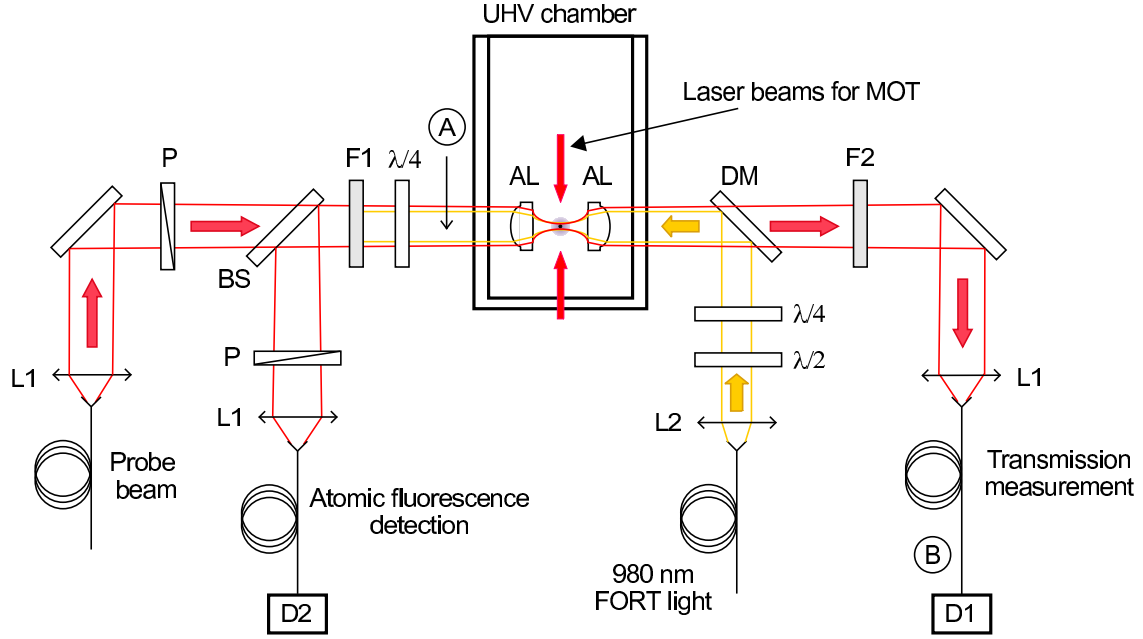


Figure 1: Experimental setup for measuring the extinction of a light beam by a single atom. AL: aspheric lens ($f = 4.5$ mm, full NA = 0.55), P: polarizer, DM: dichroic mirror, BS: beam splitter with 99% reflectivity, $\lambda/4$, $\lambda/2$: quarter and half wave plates, F1: filters for blocking the 980 nm FORT light, F2: interference filter centered at 780 nm, D1 and D2: Si-avalanche photodiodes. Four more laser beams forming the MOT lie in an orthogonal plane and are not shown explicitly.

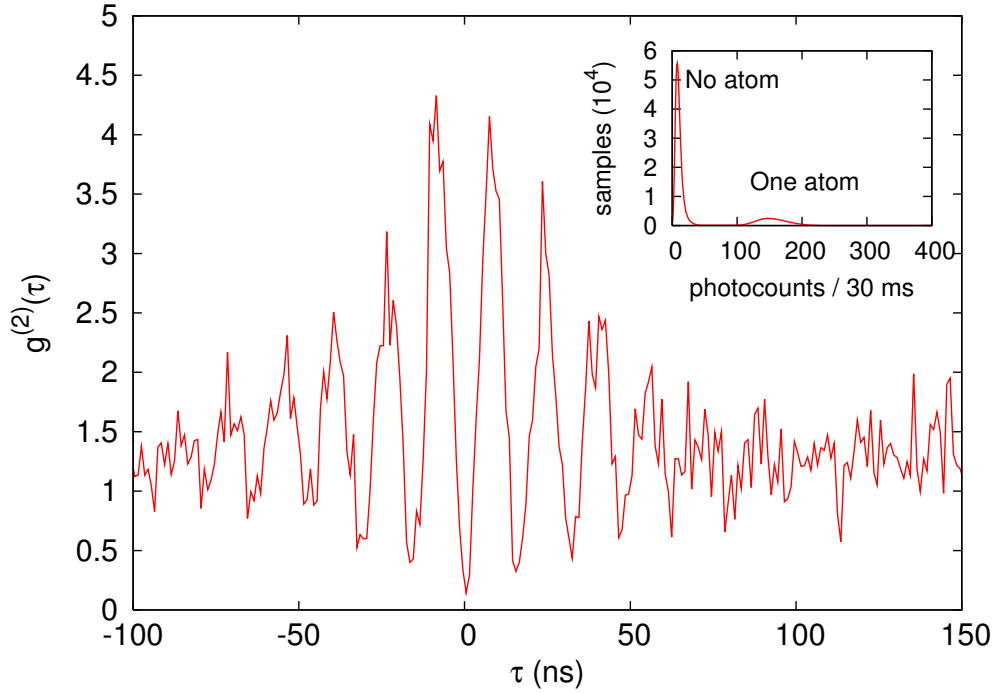


Figure 2: Normalized second-order correlation function versus time delay τ between two photodetection events at detectors D1 and D2 (not corrected for background counts) with clear antibunching at $\tau = 0$. The inset shows a histogram of photocounts from the atomic fluorescence revealing the “binary” character of the detected events due to collisional blockade²¹.

with ≈ 62 MHz and with a damping time compatible with the spontaneous decay lifetime of the 5P state in ^{87}Rb (27 ns). An almost vanishing $g^{(2)}(\tau = 0)$ indicates that no two photons are emitted at the same time from the trap region, providing strong evidence that we only have a single atom in the trap^{23–25}. The observation of a binary on/off fluorescence signal provides further evidence that there is either one or no atom in the trap at any time²¹.

We would expect to observe the largest extinction for a clean two-level system with no other decay channels. Therefore, we use a circularly polarized probe beam that optically pumps the ^{87}Rb atom to a closed-cycling transition either between $|g+\rangle = |5S_{1/2}, F=2, m_F=+2\rangle$ and $|e+\rangle = |5P_{3/2}, F'=3, m_{F'}=+3\rangle$, or between $|g-\rangle = |F=2, m_F=-2\rangle$ and $|e-\rangle = |F'=3, m_{F'}=-3\rangle$ (Fig. 3). As the MOT beams are turned off during the measurement, the atom can be heated up and even kicked out of the FORT by the probe. To avoid this problem, the intensity of the probe is reduced to a level where the actual photon scattering rate was estimated to be around 2500 s^{-1} (about five times smaller than the longitudinal oscillation frequency of the atom in the FORT). For such a low scattering rate, however, we need to ensure that the atom does not leave the cycling transition between subsequent photon scattering events. A magnetic field orthogonal to the quantization axis causes the atom to undergo Larmor precession, leaking pop-

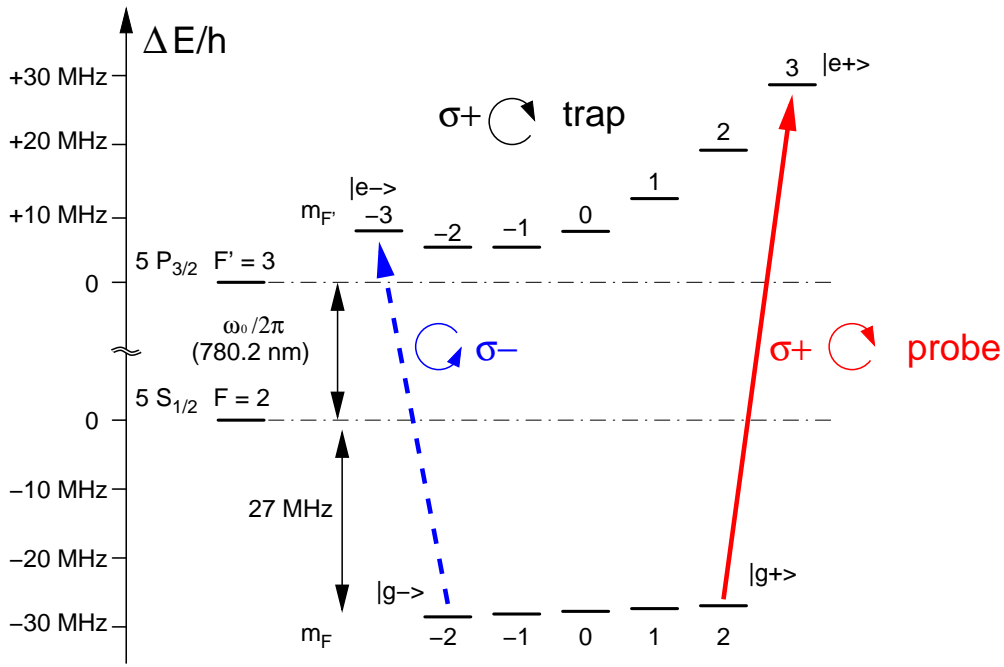


Figure 3: Predicted AC Stark shift of a ^{87}Rb atom in a circularly polarized FORT for the parameters mentioned in the text.

ulation from $|g\pm\rangle$ or $|e\pm\rangle$ to other $|m_F\rangle$, $|m_{F'}\rangle$ states, which upsets the clean two level system. To prevent this, we carefully zero the magnetic field at the location of the trapped atom, and then apply a magnetic bias field along the quantization axis during the measurement. Similarly, the FORT-induced AC Stark shift breaks the degeneracy of the hyperfine states of the trapped atom. If $|g\pm\rangle$ and $|e\pm\rangle$ (fixed through optical pumping by the probe) are not the energy eigenstates of the atom in the FORT, population also leaks out of the two-level system. Experimental evidence for this was a reduction of the observed extinction by a factor of two for linearly polarized FORT field. In our experiment, we therefore we adopt a circularly polarized FORT beam counterpropagating with the circularly polarized probe.

Figure 3 shows the calculated AC Stark shift of the $5S_{1/2}$, $F = 2$ and $5P_{3/2}$, $F' = 3$ hyperfine states of the ^{87}Rb atom under the influence of a circularly polarized FORT light of 980 nm wavelength with a trapping potential depth of $h \cdot 27$ MHz. The quantization axis of our system is chosen parallel to the main propagation axes of the probe/FORT beams and such that the polarization of the FORT field is right hand circular. A σ^+ probe refers to a circular polarization that drives the atom from $|g+\rangle$ to $|e+\rangle$, and a σ^- probe to one driving a $|g-\rangle$ to $|e-\rangle$ transition. At the center of the FORT, the energies of $5S_{1/2}$ states are lowered by an average of $h \cdot 27$ MHz (defining the trapping potential) with a small sublevel energy splitting of ≈ 1 MHz. The $5P_{3/2}$ levels shift upwards and are strongly split, forming a repulsive potential. The resulting shifts of the resonance frequency for different transitions can be observed directly in a transmission measurement in which

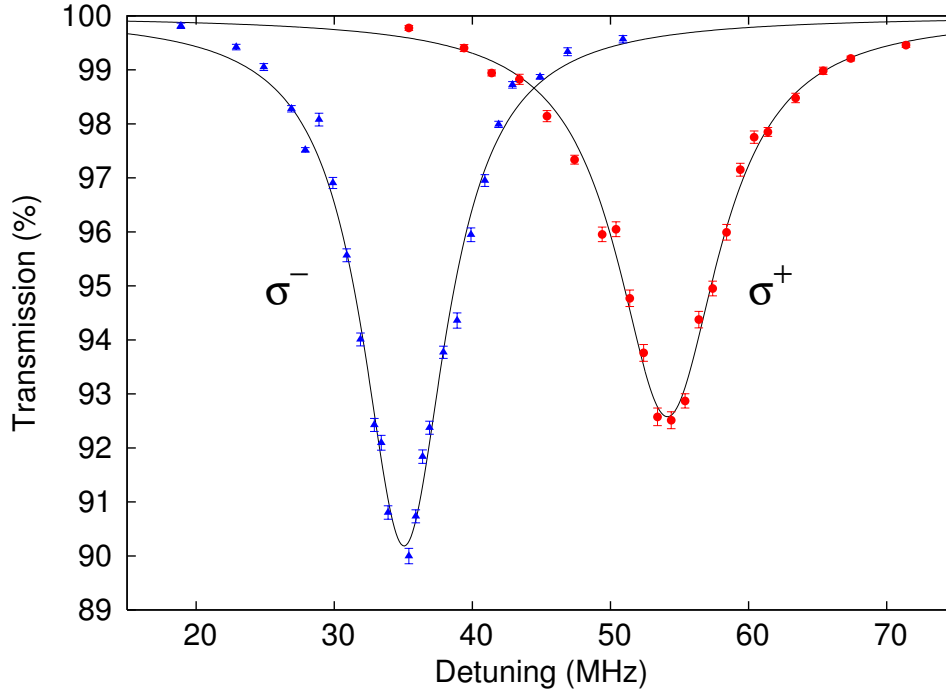


Figure 4: Transmission of the probe beam versus detuning from the natural resonant frequency $\omega_0/2\pi$ of the $|g\rangle$ to $|e\rangle$ transition. The absolute photon scattering rate is kept at $\approx 2500 \text{ s}^{-1}$ for every point by adjusting the probe intensity according to the measured extinction. The solid lines are Lorentzian fits.

the frequency of the probe is scanned over the resonance frequency of the trapped atom.

Figure 4 shows the transmission of the probe as a function of detuning from the natural resonant frequency $\omega_0/2\pi$ of the $|g\rangle$ to $|e\rangle$ transition (see methods for transmission measurement procedures). The two spectra of a single ^{87}Rb atom were obtained for σ^+ and σ^- probes, while keeping the handedness of the FORT beam fixed. As expected, the atomic resonance frequency is different for the two probe polarizations, and agrees very well with prediction shown in Figure 3. The Lorentzian fit to the transmission spectrum for the σ^- probe shows a maximum extinction of $9.8 \pm 0.2\%$ with a full-width-half-maximum (FWHM) of $7.5 \pm 0.2 \text{ MHz}$. The σ^+ probe gives a maximum extinction of $7.4 \pm 0.1\%$ with a FWHM of $9.1 \pm 0.3 \text{ MHz}$. From the fact that the D2 transition of ^{87}Rb has a natural linewidth of 6.0 MHz and that the linewidth/stability of the probe laser is about 1 MHz , we conclude that an atom exposed to the σ^- probe has been successfully kept in a two-level cycling transition, and it experiences very small spectral broadening caused by position dependent AC Stark shift in the FORT. However, the same conclusion cannot be made for the atom exposed to a σ^+ probe. A possible explanation is that optical pumping by the σ^+ probe is less effective because a probe frequency resonant to the $|g+\rangle$ to $|e+\rangle$ transition is further detuned from the resonant frequencies of other $|F = 2, m_F\rangle$ to $|F' = 3, m_{F'}\rangle$ transitions, whereas the

resonance frequency of $|g-\rangle$ to $|e-\rangle$ is less detuned from other transitions (Fig. 3). Furthermore, a FORT wavelength of 980 nm forms a repulsive potential for the $5P_{3/2}$ levels of the ^{87}Rb atom. As the energy of $|e+\rangle$ is higher than that of the $|e-\rangle$, an atom in $|e+\rangle$ experiences a stronger repulsive force from the FORT on average. As a result, a trapped ^{87}Rb atom might be more susceptible to increase of kinetic energy under the σ^+ probe, and thus oscillates more strongly around the focus.

Coming back to the photon-atom coupling efficiency, we want to emphasize that an extinction of 9.8% observed for a probe focused to ≈ 860 nm waist²⁶ is large when compared to results reported from experiments performed on single molecules and quantum dots^{16–18}. There, the excitation light field was either confined with a small aperture of ≈ 100 nm¹⁶, or focused by using solid immersion lenses^{17,18} that provide much tighter focusing than in our case. In all these experiments quantum systems were embedded into complex solid state host environments which complicates the theoretical treatment of light scattering. The conceptual simplicity of the system we investigate and the fact that we directly measure the extinction of the probe beam allows a clean comparison with existing photon-atom coupling models^{13,14,19}.

One of the models that closely describes our experiment was presented by van Enk and Kimble¹³. It considers a monochromatic and circularly polarized Gaussian beam focused by an ideal thin lens onto a two-level atomic system. Estimations based on that model gave a very dim outlook on the effectiveness of coupling light to an atom using a lens. In particular, a direct application of the method described there predicts a maximum scattering probability of 2.2% for our experimental parameters. As it turns out, two approximations adopted in the model (parabolic wave front after the lens, and no change to the polarization of a light beam passing through the lens) has greatly underestimated scattering probability for stronger focusing. Dropping these approximations, we find (with otherwise same methods) a scattering probability of 20.3% for our experimental parameters²⁰. The residual difference between the predicted and measured values could be both due to the imperfections of our aspheric lens, and the fact that the atom is not completely stationary at the focus. Applying this model for an even tighter focus, a very high scattering probability of up to 95% is predicted (for focusing $\text{NA} \approx 0.9$)²⁰. Such a high scattering probability is at odd with other photon-atom coupling models which suggest a maximum scattering probability of 50% for a light beam focused by a lens as in our setup^{14,19}; further experimental work is required to check this discrepancy.

In conclusion, we experimentally observed a substantial extinction of a weak coherent light field by a single atom by focusing the light beam using a lens. In particular, a coupling efficiency of at least 9.8% has been achieved with a focused beam waist of $\approx 0.86 \mu\text{m}$. Such values might appear to be small compared to the maximum achievable with the help of a cavity. In practice, however, due to mode-matching issues and other passive losses, achieving very good coupling of light into a high finesse cavity is nontrivial. This problem reduces the overall photon-atom coupling efficiency between a truly 'flying' qubit and an atom when using a cavity¹⁰. Contrary, a lens system suffers much less from reflection losses. This advantage, together with the simplicity of such configuration would make such a photon-atom coupling scheme very appealing to many applications involving

quantum state transfer from photons to atoms. Furthermore, the strong interaction of the atom with a flying qubit suggests using the atom as a mediator for a photon-photon interactions, pointing in a new direction for implementing photonic quantum gates.

Methods

Direct extinction measurements

In general, extinction is obtained by comparing the transmitted power of the probe with and without the sample in the optical path of the probe. In usual extinction measurements, e.g. as implemented in a commercial spectrophotometer, the probe beam is collected fully by the power measuring device. However, this is not the case in the extinction measurements on single quantum systems reported so far, e.g. in^{16–18}. The reason is that substantial extinction of a probe beam by single quantum systems generally requires strong focusing. It is, nevertheless, difficult if not impossible in most experiments to collect the strongly diverging probe fully after the focus. As such, the ‘extinction’ measured in such experiments is not the extinction in the usual sense and cannot be used in a straightforward way to quantify the actual scattering probability of the probe by the quantum system without further model assumptions. In our experiment, we collect all of the diverging probe light, and thus are able to carry out a *direct* extinction measurement.

The measured transmission T is related to the scattering probability P_{sc} by $T = 1 - P_{sc} + \alpha P_{sc}$, where α represents the percentage of scattered light collected by the transmitted power detector. The extinction $\epsilon = 1 - T$ is thus related to the scattering probability by $P_{sc} = \epsilon / (1 - \alpha)$. The collection efficiency α in this experiment is estimated to be less 5%, so $P_{sc} \approx \epsilon$.

Losses and interference artefacts

We carefully quantified the losses in the transmission channel to make sure our results do not suffer from interference artefacts (interference between partially collected probe and scattered light can lead to value of ‘extinction’ larger than the scattering probability). The total transmission from point A in Fig. 1 (before the vacuum chamber) to point B (after the single-mode fiber and just before the detector) is 53%. The 47% loss include 21.6% loss from the four uncoated window surfaces of the vacuum chamber and the two aspheric lenses; 5.3% loss over two dichroic mirrors, an interference filter (peak transmission $T=96\%$ at 780 nm) and a mirror; and 28.4% coupling loss into an uncoated single mode fiber. All the losses are caused by reflection except for 20% loss at the fiber coupling that is due to imperfect mode matching. Since the scattered field and the probe field should experience the same reflection loss at each surface, we are reasonably confident that our results are free from interference artefacts.

Sequence for transmission measurement

Once an atom is loaded into the FORT, it triggers the transmission measurement sequence. The main steps include: step 1. Switching off the MOT beams and the MOT quadrupole coil current; step 2. Application of a magnetic bias field of ≈ 2 G along the quantization axis; step 3. Waiting for 20 ms so that current in the coils stabilizes and optically pumping the atom into either $|g+\rangle$ or $|g-\rangle$ at the same time; step 4. Recording the photo counts n_m of the transmitted probe beam for τ_m ranging from 130 to 140 ms with detector D1; step 5. Switching on the MOT beams to check whether the atom is still in the FORT by monitoring fluorescence with detector D2; if “yes”, turn off the MOT beams and repeat step 3 and 4; step 6. Otherwise, recording the photo counts n_r of the transmitted probe beam with detector D1 for $\tau_r = 2$ s without an atom in the trap for reference; step 7. Turning on the MOT beams and the quadrupole coil current, waiting for another atom to be loaded in the FORT.

A transmission value T is obtained for each atom trapping event by $T = \frac{\sum n_m \tau_r}{\sum \tau_m n_r}$, where the summation is carried over all contiguous measurement intervals m for which an atom was found in the trap. The average time an atom stays in the FORT is about 1.5 s. A single data point in figure 4 is the average of about 100 of such transmission values, each weighted by $\frac{\tau_r \sum \tau_m}{\tau_r + \sum \tau_m}$.

The error is dominated by photo counting shot noise, our error bars indicate ± 1 standard deviation. During the transmission measurement process, the atom may fall into the $|5S_{1/2}, F = 1\rangle$ metastable ground state, which is off resonant with the probe. To bring it back to the pumping cycle, circularly polarized light resonant with the D1 transition is mixed into the probe beam, and later removed with an interference filter F2 (Fig. 1).

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